

# Progress Report: ECR Ion Source and LEBT Development for the RIA Driver Linac

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## Summary

Significant progress has been made on the VENUS project during FY04. In 2003, the successful commissioning at 18 GHz was completed. First systematic emittance measurements were done at RIA relevant intensities using Bi. At 2kW 18 GHz microwave power, we were able to exceed the RIA base line intensity requirements (assuming a 2 charge state LEBT) for Bi by simultaneously meeting the emittance specifications (see Table 2). More than 6 pμA of Bi<sup>24+</sup> and Bi<sup>25+</sup> could be extracted at a 1rms emittance of less than .12 π·mm·mrad. In May 2004, 28 GHz was coupled into the VENUS source for the first time. At initial operation more than 16 pμA of Xe<sup>20+</sup> (twice the amount extracted at 18 GHz), 10 pμA of Bi<sup>24+</sup> and Bi<sup>25+</sup>, and 8.6 pμA of Bi<sup>29+</sup> were extracted. The promising performance at 28 GHz opens the possibility to increase the charge state requirement for the RIA accelerator, which would reduce the costs of the driver linac. Table 1 summarizes the major milestones and project achievements. In addition, we are developing simulation tools based on parallel supercomputing simulations, which will allow modeling the highly space-charge-dominated, multiple species and multi-charged heavy ion beams from the ECR ion source through the LEBT and the analyzing magnet. Within the last six months we have developed a three-dimensional multigrid Poisson solver and novel charge deposition algorithm for code. Following these enhancements of the IMPACT code, we are planning to start systematic simulation for the VENUS LEBT in the near future.

Table 1 summarizes the major milestones and project achievements

Major Milestones and Achievements	Milestone	Achieved
18 GHz operation: 6 pμA Bi <sup>24+</sup> and Bi <sup>25+</sup> , 8 pμA Xe <sup>20+</sup>		9/03
Modification of the cryostat (add third cryocooler)	12/1/04	11/27/03
Systematic emittance for Bi <sup>24+</sup> -Bi <sup>41+</sup> measurements at 18 GHz		2/8/04
Testing of 28 GHz microwave components at the factory	12/1/03	9/27/03
Gyrottron System Delivery	3/15/04	5/15/04
First 28 GHz plasma	6/1/04	5/26/04
First emittance measurements at 28 GHz	6/1/04	5/27/04
28 GHz operation: 16 pμA Xe <sup>20+</sup> , 10 pμA Bi <sup>24+</sup> and Bi <sup>25+</sup> , 8.6 pμA Bi <sup>29+</sup>		6-8/04

## RIA R&D on VENUS

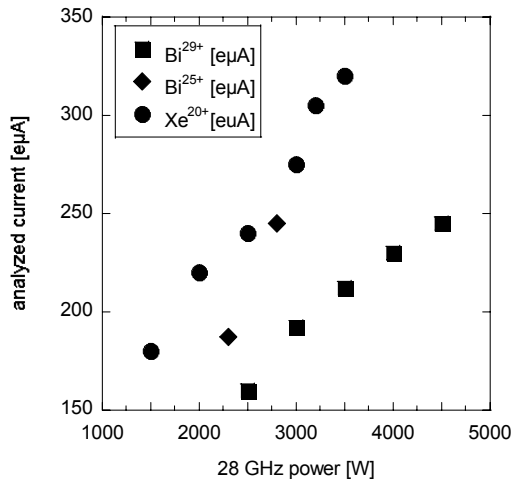
During the 18 GHz commissioning period, a number of improvements were made to the cryostat system, the 18 GHz microwave system, and the magnet power supply control system [1-3]. As a result of these improvements, VENUS is now operational at the full capacity of the 2 kW, 18 GHz klystron. The operation experience has been excellent in terms of stability, reproducibility, and reliability. At initial 18 GHz operation, intense high charge state beams such as 1100 eμA of O<sup>6+</sup>, 160 eμA of Bi<sup>25+</sup> and 11 eμA of Bi<sup>41+</sup> have been extracted easily. Systematic emittance measurements have been performed during the months of January and February 2004 for medium to high charge state Bi ions with focus on RIA relevant intensities and charge states. Bismuth was chosen since its mass is close to uranium. Consequently, the extraction, and ion beam transport characteristics are very similar. However, bismuth is less reactive than uranium, not radioactive, and evaporates at

modest temperatures. Furthermore, it has only one isotope and provides a clean spectrum for systematic emittance measurements. At 2kW 18 GHz microwave power, we were able to exceed the RIA base line intensity requirements (assuming a 2 charge state LEBT) for Bi by simultaneously meeting the emittance specifications (see Table 1). [4]

Parallel to the commissioning at 18 GHz, preparations for the 28 GHz operations were made. The cryostat was extended and a third cryocooler was installed. In addition, provisions for a fourth cryocooler have been added to the cryostat. The present system provides up to 2 W of cooling power to remove heat generated by bremsstrahlung, which is produced by the plasma electrons and deposited in the cryostat. However, the preliminary 28 GHz tests showed that improved x-ray shielding will be necessary to run VENUS at full capacity of the 10 kW 28 GHz gyrotron power supply. We are planning to implement this additional x-ray shielding in FY05.

The 28 GHz components and the gyrotron tube were successfully tested in December 2003 at the CPI factory in Palo Alto. The gyrotron system was shipped to LBNL end of April and installed by CPI in the middle of May. The first 28 GHz plasma was ignited in May 2004. The preliminary results have been very promising: Already in early June 1.2 mA of  $O^{6+}$  and 320  $\mu A$  of  $Xe^{20+}$  (twice the amount extracted at 2kW of 18 GHz in case of Xe) have been extracted. Fig. 1 shows the analyzed current dependency to the microwave power coupled into the plasma for a few sample ion beams. To date is the maximum power injected into the source is 4.5 kW, but the almost linear increase in current for all the ions with rf power shows that 4.5 kW is well below the saturation point.

**Fig.1** Dependence of the extracted current for several ions to the coupled 28 GHz microwave power.



**Table 1:** Preliminary commissioning results of VENUS at 18 GHz and 28 GHz in comparison with the double frequency heated AECR-U [5].

$f$ (GHz)		VENUS	VENUS	AECR-U
		28	18	10+14
$^{16}O$	6 <sup>+</sup>	1200	1100	840*
	7 <sup>+</sup>	>360	324	360*
Xe	20 <sup>+</sup>	320	164	
	27 <sup>+</sup>	120	84	30
Bi	24 <sup>+</sup>	243		
	25 <sup>+</sup>	243	160	70
	27 <sup>+</sup>		150	75
	28 <sup>+</sup>	240	128	60
	29 <sup>+</sup>	245	115	55
	30 <sup>+</sup>	225	102	57
	31 <sup>+</sup>	203	86	48
	32 <sup>+</sup>	165	60	41

In August 2004, the first high intensity metal ion beams were produced again using bismuth. More than 240 $\mu A$  (10  $\mu A$ ) of  $Bi^{24+}$  and  $Bi^{25+}$  were produced exceeding the base line requirements for RIA for this particular beam without the necessity of a two charge state LEBT. Further tests showed that the charge state can be shifted 5 charges up to  $Bi^{29+}$ , while still fulfilling the RIA intensities using only a single charge state in the LEBT. This opens the possibility to increase the charge state requirement for the RIA accelerator, which would reduce the costs of the driver linac. Preliminary emittance measurements have been performed for high intensity Bi ion beams at RIA relevant intensities and these emittance values meet the RIA specifications. Table 1 states the initial performance of VENUS at 18

GHz and preliminary results at 28 GHz for oxygen, xenon, and bismuth. For comparison, data from the LBNL AECR-U 14 GHz ECR ion source are also included.

In addition, we are developing simulation tools based on parallel supercomputing simulations, which will allow modeling the highly space-charge-dominated, multiple species and multi-charged heavy ion beams from the ECR ion source through the LEBT and the analyzing magnet. A crucial part of this effort will be the combination of the measured ion beam characteristics with the ion beam simulation to develop an accurate computational model for the ECR ion source LEBT design and optimization. A postdoc was hired in June to work closely with a staff scientist from the Center of Beam Physics on the project. Within the last six months we have developed a three-dimensional multigrid Poisson solver, which can handle varied electrode geometries (with azimuthally symmetry) of electrodes and arbitrary beam distribution in the extraction region. The multigrid numerical method uses multiple mesh resolution to smooth out the numerical errors of different frequencies. This method has significantly improved the speed of solution by more than a factor of 10 compared with the conventional successive over-relaxation method (SOR) used in many ion optics design codes [6-8]. The convergence rate of multigrid solver can be independent of the mesh size of computational domain while the conventional SOR method suffers from a slower convergence rate with a finer mesh size. This solver has been implemented and tested in the three-dimensional parallel beam dynamics code, IMPACT [9], including external solenoid fields. Besides the Poisson solver, we have also developed three charge deposition schemes to calculate the charge density on the computational grid. Following these enhancements of the IMPACT code, we are planning to start systematic simulation for the VENUS LEBT in the near future.

### **Summary of expenditures**

For FY04 a total of 685k\$ (estimating was 22k\$ for September 2004) spend on RIA R&D funds. This includes the purchase of the gyrotron system, which was funded by previous R&D funds. With the remaining funds we are planning to complete our R&D goals by March 2005.

### **Future plans**

During FY05 we are planning to continue the commissioning at 28 GHz power levels of up to 10 kW. A major focus will be the design and construction of an improved plasma chamber that is able to absorb the high power x-ray radiation emitted from the ECR plasma. First test for the production of uranium ion beams are planned for FY05 to verify the performance measured for Bi also for U. In addition, we are planning to perform systematic emittance measurements for various ion beams at 18 and 28 GHz combined with an enhanced simulation effort to establish the tools to design the LEBT for the RIA front end

### **References**

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